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## **J/ψ Elliptic Flow in Pb-Pb Collisions at $\sqrt{s_{NN}} = 2.76$ TeV**

The ALICE Collaboration\*

### **Abstract**

We report on the first measurement of inclusive J/ψ elliptic flow,  $v_2$ , in heavy-ion collisions at the LHC. The measurement is performed with the ALICE detector in Pb-Pb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV in the rapidity range  $2.5 < y < 4.0$ . The dependence of the J/ψ  $v_2$  on the collision centrality and on the J/ψ transverse momentum is studied in the range  $0 \leq p_T < 10$  GeV/c. For semi-central Pb-Pb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV, an indication of non-zero  $v_2$  is observed with a maximum value of  $v_2 = 0.116 \pm 0.046(\text{stat.}) \pm 0.029(\text{syst.})$  for J/ψ in the transverse momentum range  $2 \leq p_T < 4$  GeV/c. The elliptic flow measurement complements the previously reported ALICE results on the inclusive J/ψ nuclear modification factor and favors the scenario of a significant fraction of J/ψ production from charm quarks in a deconfined partonic phase.

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\*See Appendix A for the list of collaboration members

The aim of ultra-relativistic heavy nuclei collisions is the study of nuclear matter at high temperature and pressure where Quantum Chromodynamics predicts the existence of a deconfined state of partonic matter, the Quark-Gluon Plasma (QGP). Heavy quarks are expected to be produced in the primary partonic scatterings and to interact with this partonic medium making them ideal probes of the QGP. The measurement of quarkonium states and hadrons with open heavy flavor is therefore expected to provide essential information on the properties of the strongly-interacting system formed in the early stages of heavy-ion collisions [1]. According to the color-screening model [2], quarkonium states will be suppressed in the medium with different dissociation probabilities for the various states. Recently, the CMS Collaboration at the Large Hadron Collider (LHC) reported about the observation of the sequential suppression in the  $\Upsilon$  sector [3]. The ALICE Collaboration published the inclusive J/ψ nuclear modification factor  $R_{AA}$  down to zero transverse momentum ( $p_T$ ) at forward rapidity in Pb-Pb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV [4]. The  $R_{AA}$  compares the yields in Pb-Pb to those in pp collisions scaled by the number of binary nucleon-nucleon collisions. The inclusive J/ψ nuclear modification factor reported is larger than that measured at the SPS [5] and at RHIC [6, 7] for central collisions and does not exhibit a significant centrality dependence. Complementarily, the CMS Collaboration measures the high  $p_T$  ( $6.5 \leq p_T < 30$  GeV/c) prompt J/ψ  $R_{AA}$  in Pb-Pb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV in the rapidity range  $|y| < 2.4$  [8]. The data of CMS shows that high  $p_T$  J/ψ are found to be more suppressed than low  $p_T$  J/ψ and that this suppression does exhibit a strong centrality dependence.

The weak centrality dependence of the J/ψ  $R_{AA}$  at low transverse momentum can be qualitatively understood with models including full [9, 10] or partial [11, 12] regeneration of J/ψ from deconfined charm quarks in the medium. The J/ψ regeneration mechanism was first proposed by the Statistical Hadronization Model (SHM), which assumes deconfinement and thermal equilibrium of the bulk of  $c\bar{c}$  pairs to produce J/ψ at the phase boundary by statistical hadronization only [9]. Later, the transport models proposed a dynamical competition between the J/ψ suppression by the QGP and the regeneration mechanism, which enables them to describe also the  $p_T$  dependence of the J/ψ  $R_{AA}$  [11, 12]. These models have in common the assumption of deconfinement and some degree of charm quark thermalization. More differential studies, like the J/ψ elliptic flow, could help to assess the charm quark thermalization in the medium.

The azimuthal distribution of particles in the plane perpendicular to the beam direction is an experimental observable also sensitive to the dynamics of the early stages of heavy-ion collisions. When nuclei collide at finite impact parameter (non-central collisions), the geometrical overlap region and, therefore, the initial matter distribution is anisotropic (almond-shaped). If the matter is strongly interacting, this spatial asymmetry is converted via multiple collisions into an anisotropic momentum distribution [13]. The second coefficient of the Fourier expansion describing the final state particle azimuthal distribution with respect to the reaction plane,  $v_2$ , is called elliptic flow. The reaction plane is defined by the beam axis and the impact parameter vector of the colliding nuclei.

Within the transport model scenario [11, 12] the observed J/ψ have two origins. First, primordial J/ψ, which are produced in the initial hard scatterings, traverse and interact with the created medium. During this process they may be dissociated. Second, J/ψ could be regenerated from deconfined charm quarks and anti-quarks in the QGP. Primordial J/ψ emitted in-plane traverse a shorter path through the medium than those emitted out-of-plane resulting in a small azimuthal anisotropy for the surviving J/ψ. Regenerated J/ψ inherit the elliptic flow of the charm quarks in the QGP. If charm quarks do thermalize in the QGP then J/ψ formed there can exhibit a significant elliptic flow.

At RHIC energies, the (preliminary) measurements by the (PHENIX) STAR Collaboration of the J/ψ elliptic flow in Au-Au collisions at  $\sqrt{s_{NN}} = 200$  GeV [14, 15] are consistent with zero albeit with large uncertainties in the  $p_T$  and centrality ranges (0–5 GeV/c) 2–10 GeV/c and (20%–60%) 10%–50%. The measurement of quarkonium elliptic flow is especially promising at the LHC where the high energy density of the medium and the large number of  $c\bar{c}$  pairs produced in Pb-Pb collisions should favor the development

of flow and the regeneration mechanisms.

In this Letter, we report ALICE results on inclusive J/ψ elliptic flow in Pb-Pb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV at forward rapidity, measured via the  $\mu^+\mu^-$  decay channel. The J/ψ elliptic flow is presented as a function of transverse momentum and collision centrality.

The ALICE detector is described in [16]. At forward rapidity ( $2.5 < y < 4$ ) the production of quarkonium states is measured via the decay channel  $\mu^+\mu^-$  in the muon spectrometer<sup>1</sup> down to  $p_T = 0$ . The spectrometer consists of a ten interaction length thick absorber stopping the hadrons in front of five tracking stations comprising two planes of cathode pad chambers each, with the third station inside a dipole magnet delivering a 3 Tm field integral. The tracking apparatus is completed by a triggering system made of four planes of resistive plate chambers downstream of a 1.2 m thick iron wall, which absorbs secondary hadrons escaping from the front absorber and low momentum muons coming mainly from  $\pi$  and K decays. In addition, the silicon pixel detector (SPD) and scintillator arrays (VZERO) were used in this analysis. The VZERO counters consist of two arrays of 32 scintillator sectors each distributed in four rings covering  $2.8 \leq \eta \leq 5.1$  (VZERO-A) and  $-3.7 \leq \eta \leq -1.7$  (VZERO-C). The SPD, used to determine the location of the interaction point, consists of two cylindrical layers covering  $|\eta| \leq 2.0$  and  $|\eta| \leq 1.4$  for the inner and outer layers, respectively. All of these detectors have full azimuthal coverage. The data sample used for this analysis, collected in 2011, amounts to  $17 \times 10^6$  dimuon unlike sign (MU) triggered Pb-Pb collisions and corresponds to an integrated luminosity  $\mathcal{L}_{int} \approx 70 \mu\text{b}^{-1}$ . In addition to a minimum bias (MB) trigger, the MU trigger requires at least a pair of opposite sign track segments, each with a  $p_T$  above the threshold of the on-line trigger algorithm. The  $p_T$  threshold of the trigger algorithm was set to provide 50% efficiency for muon tracks with  $p_T = 1$  GeV/c. The MB trigger requires a signal in VZERO-A and a signal in VZERO-C. The beam induced background was further reduced offline using the VZERO and the zero degree calorimeter (ZDC) timing information. The contribution from electromagnetic processes was removed by requiring a minimum energy deposited in the neutron ZDCs [17]. The centrality determination is based on a fit of the VZERO amplitude distribution as described in [18]. A cut corresponding to the most central 90% of the nuclear cross section was applied; for these events the MB trigger is fully efficient and the contribution from electromagnetic processes is negligible.

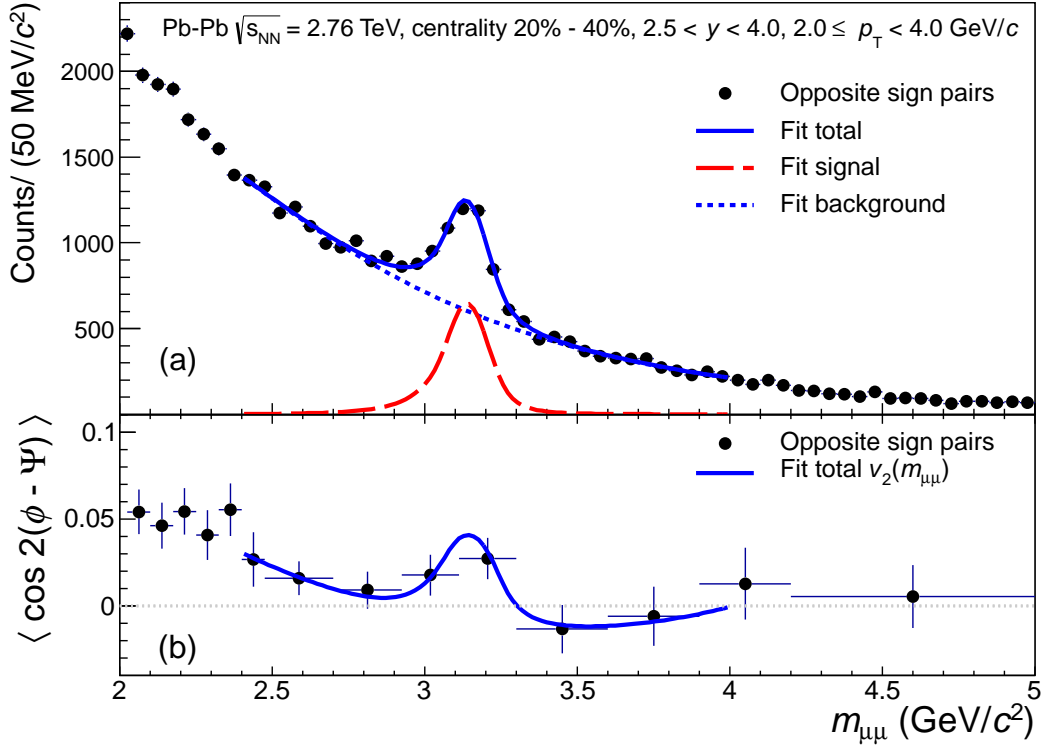
J/ψ candidates are formed by combining pairs of opposite-sign (OS) tracks reconstructed in the geometrical acceptance of the muon spectrometer. To improve the muon identification, the reconstructed tracks in the muon tracking chambers are required to match a track segment in the muon trigger system above the  $p_T$  threshold of the on-line trigger algorithm.

The J/ψ  $v_2$  is calculated using event plane (EP) based methods. The azimuthal angle  $\Psi$  of the second harmonic event plane is used as an estimate of the reaction plane angle [19].  $\Psi$  is determined from the azimuthal distribution of the VZERO amplitude. The VZERO-C has a common acceptance region with the muon spectrometer. Therefore, only the VZERO-A was used for the event plane determination to avoid autocorrelations. The J/ψ  $v_2$  results were obtained determining  $v_2 = \langle \cos 2(\phi - \Psi) \rangle$  versus invariant mass ( $m_{\mu\mu}$ ) [20], where  $\phi$  is the dimuon azimuthal angle. In this method,  $v_2$  of the OS dimuons is calculated as a function of  $m_{\mu\mu}$  and then the resulting  $v_2(m_{\mu\mu})$  distribution is fitted using:

$$v_2(m_{\mu\mu}) = v_2^{\text{sig}} \alpha(m_{\mu\mu}) + v_2^{\text{bkg}}(m_{\mu\mu})[1 - \alpha(m_{\mu\mu})], \quad (1)$$

where  $v_2^{\text{sig}}$  and  $v_2^{\text{bkg}}$  correspond to the  $v_2$  of the J/ψ signal and of the background, respectively.  $v_2^{\text{bkg}}$  was parametrized using a second order polynomial (see Fig. 1 (b)). Here,  $\alpha(m_{\mu\mu}) = S/(S+B)$  is the ratio of the signal over the sum of the signal plus background of the  $m_{\mu\mu}$  distributions. It is extracted from fits to the OS invariant mass distribution (see Fig. 1 (a)) in each  $p_T$  and centrality class. The OS dimuon invariant mass distribution was fitted with a Crystal Ball (CB) function to reproduce the J/ψ line shape,

<sup>1</sup>In the ALICE reference frame, the muon spectrometer covers a negative  $\eta$  range and consequently a negative  $y$  range. We have chosen to present our results with a positive  $y$  notation.



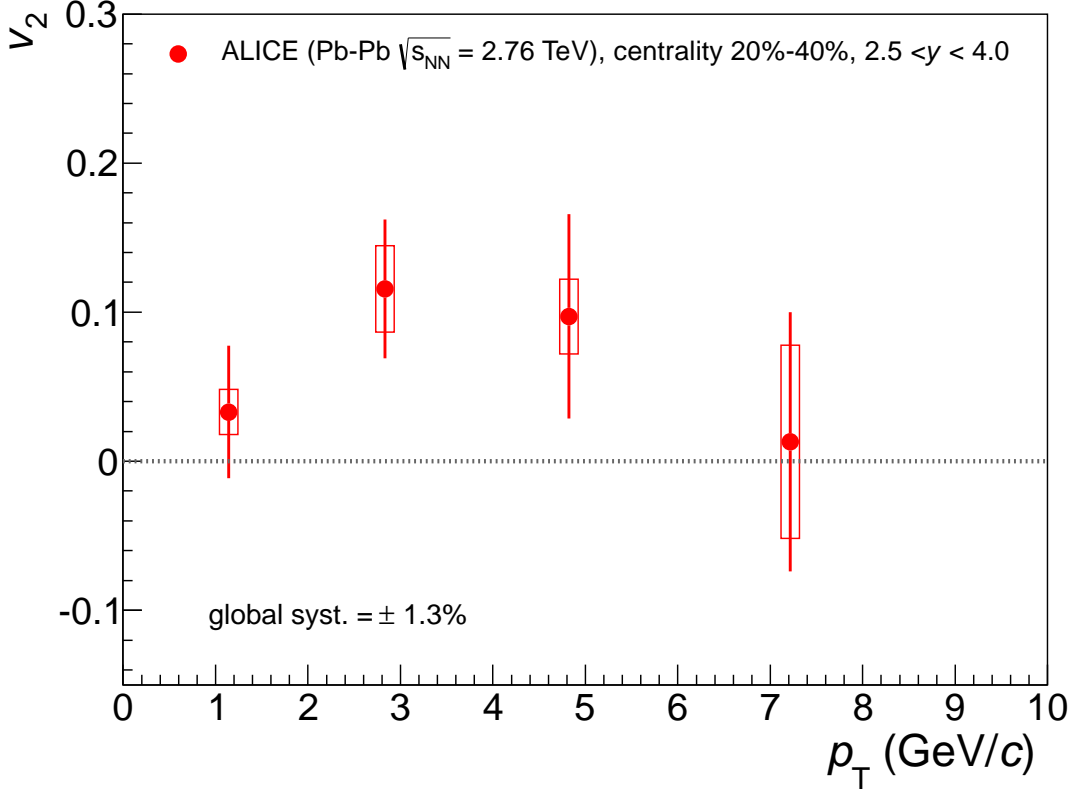
**Fig. 1:** (Color online) Invariant mass spectrum (a) and  $\langle \cos 2(\phi - \Psi) \rangle$  (b) as a function of the invariant mass of  $\mu^+\mu^-$  pairs (fitted with Eq. 1) with  $2 \leq p_T < 4$  GeV/c and  $2.5 < y < 4$  in the 20%–40% semi-central Pb-Pb collisions.

and either a third order polynomial or a gaussian with a width linearly varying with mass to describe the underlying continuum. The CB function connects a Gaussian core with a power-law tail [21] at low mass to account for energy loss fluctuations and radiative decays. An extended CB function with an additional power-law tail at high mass, to account for alignment and calibration biases, was also used. The combination of several CB and underlying continuum parametrizations described before were tested to assess the signal and the related systematic uncertainties. The J/ψ  $v_2$  and its statistical uncertainty in each  $p_T$  and centrality class were determined as the average of the  $v_2^{\text{sig}}$  obtained by fitting  $v_2(m_{\mu\mu})$  using Eq. 1 with the various  $\alpha(m_{\mu\mu})$ , while the corresponding systematic uncertainties were defined as the RMS of these results. Figure 1 shows typical fits of the OS invariant mass distribution (a) and of the  $\langle \cos 2(\phi - \Psi) \rangle$  as a function of  $m_{\mu\mu}$  (b) in the 20%–40% centrality class. The systematic uncertainty related to the unknown shape of the  $v_2^{\text{bkg}}(m_{\mu\mu})$  was evaluated by repeating the procedure above using either a first order polynomial or its inverse as  $v_2^{\text{bkg}}$  parametrization. The largest deviation of the results obtained with the three different  $v_2^{\text{bkg}}$  parametrizations was conservatively adopted as the systematic uncertainty. A similar method is used to extract the uncorrected (for detector acceptance and efficiency) average transverse momentum ( $\langle p_T \rangle^{\text{uncor}}$ ) of the reconstructed J/ψ in each centrality and  $p_T$  class. The  $\langle p_T \rangle^{\text{uncor}}$  is used to locate the data points when plotted as a function of transverse momentum. Consistent  $v_2$  values were obtained using an alternative method [19] in which the J/ψ raw yield is extracted, as described before, in bins of  $(\phi - \Psi)$  and the  $v_2$  values are evaluated using a fit to the data with the function  $\frac{dN}{d(\phi - \Psi)} = A[1 + 2v_2 \cos 2(\phi - \Psi)]$ , where  $A$  is a normalization constant.

The finite resolution in the event plane determination smears out the azimuthal distributions and leads to a lower value for the measured anisotropy [19]. The VZERO-A event plane resolution as a function of the centrality was determined using MB events and the 3 sub-event method [19]. To estimate the systematic uncertainty from the event plane determination two sets of 3 sub-events were used: first, VZERO-A,

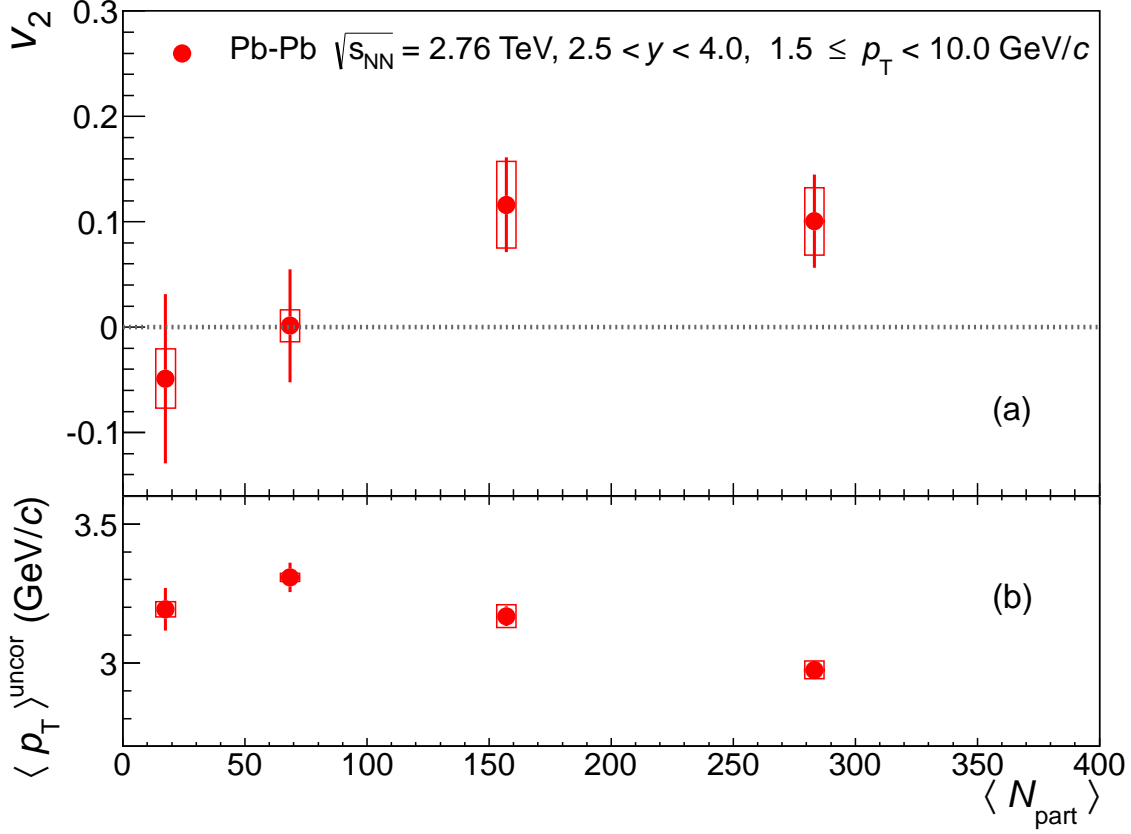
**Table 1:** VZERO-A event plane resolution for the centrality classes expressed in percentages of the nuclear cross section [18].

Centrality	$\langle N_{part} \rangle$	EP resolution $\pm$ (stat.) $\pm$ (syst.)
5%–20%	$283 \pm 4$	$0.548 \pm 0.003 \pm 0.009$
20%–40%	$157 \pm 3$	$0.610 \pm 0.002 \pm 0.008$
40%–60%	$69 \pm 2$	$0.451 \pm 0.003 \pm 0.008$
60%–90%	$15 \pm 1$	$0.185 \pm 0.005 \pm 0.013$
20%–60%	$113 \pm 3$	$0.576 \pm 0.002 \pm 0.008$

**Fig. 2:** (Color online) Inclusive J/ψ  $v_2(p_T)$  for semi-central (20%–40%) Pb-Pb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV. The  $v_2$  was measured in the  $p_T$  ranges: 0–2, 2–4, 4–6 and 6–10 GeV/c and the points are located at the measured  $\langle p_T \rangle^{uncor}$ .

VZERO-C and the Time Projection Chamber (TPC), with pseudo-rapidity gaps  $\Delta\eta_{V0A-TPC}=1.9$  and  $\Delta\eta_{TPC-V0C}=0.8$ ; second, VZERO-A, VZERO-C-1st ring and VZERO-C-4th ring, with pseudo-rapidity gaps  $\Delta\eta_{V0A-V0C1}=4.5$  and  $\Delta\eta_{V0C1-V0C4}=1.1$ . The differences between the event plane resolution for VZERO-A obtained from these two sets of sub-events are taken as systematic uncertainties. Since  $v_2$  is measured here in a wide centrality class, the resolution must reflect the distribution of events with a J/ψ within the class. Therefore, the event plane resolution for each wide class was calculated as the average of the values obtained in finer centrality classes weighted by the number of reconstructed J/ψ. Table 1 shows the corresponding resolution for each centrality class which is applied to the results reported in this Letter.

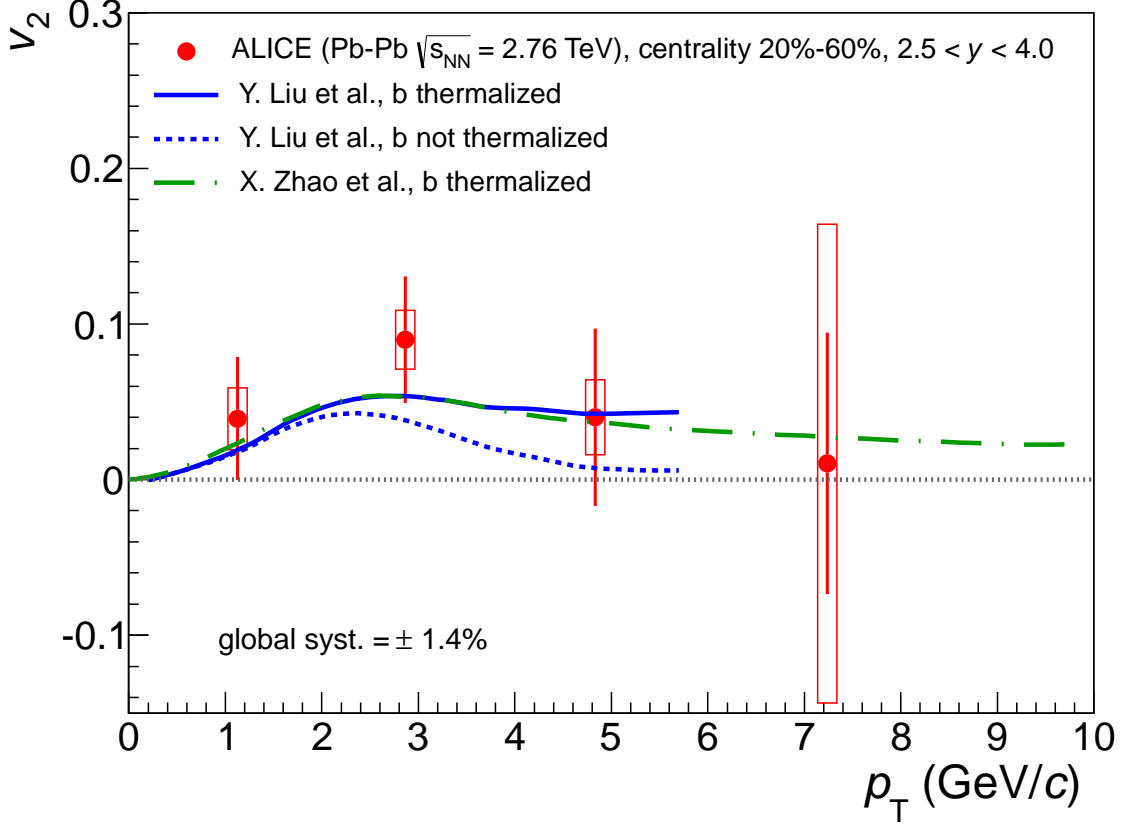
The J/ψ reconstruction efficiency depends on the detector occupancy which could result in a bias of the  $v_2$  measurement. This effect was evaluated by embedding azimuthally isotropic simulated J/ψ  $\rightarrow \mu^+\mu^-$  decays into real events. The measured  $v_2$  of those embedded J/ψ was found not to deviate from zero by more than 0.015 in all the centrality and  $p_T$  classes considered in this Letter. This value is used as a conservative systematic uncertainty on all measured  $v_2$  values.



**Fig. 3:** (Color online)  $v_2$  (a) and  $\langle p_T \rangle^{uncor}$  (b) of inclusive J/ψ with  $1.5 \leq p_T < 10$  GeV/c as a function of the number of participating nucleons in Pb-Pb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV.

Figure 2 shows the transverse momentum dependence of the inclusive J/ψ  $v_2$  for semi-central (20%–40%) Pb-Pb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV. The vertical bars show the statistical uncertainties while the boxes indicate the point-to-point uncorrelated systematic uncertainties, which include the uncertainties from the signal extraction, the  $v_2^{bkg}$  shape and from the reconstruction efficiency. The global correlated relative systematic uncertainty on the event plane resolution is 1.3%. A non-zero  $v_2$  is observed in the intermediate transverse momentum range  $2 \leq p_T < 6$  GeV/c. Taking into account statistical and systematic uncertainties the combined significance of a non-zero  $v_2$  in this  $p_T$  range is  $2.7\sigma$ . At lower and higher transverse momentum the inclusive J/ψ  $v_2$  is compatible with zero within uncertainties.

To study the centrality dependence of the  $v_2$  we select J/ψ with  $1.5 \leq p_T < 10$  GeV/c for which the signal to background ratio as well as the observed  $v_2$  are maximized. Since the initial spatial anisotropy for head-on collisions is small, the expected elliptic flow is also small. Therefore, we do not consider the 0%–5% centrality range. Figure 3 (a) shows  $v_2$  for inclusive J/ψ with  $1.5 \leq p_T < 10$  GeV/c as a function of the number of participating nucleons in Pb-Pb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV. The average number of participant nucleons  $\langle N_{part} \rangle$  for the centrality classes used in this analysis are derived from a Glauber model calculation [18]. The vertical bars show the statistical uncertainties while the boxes indicate the point-to-point uncorrelated systematic uncertainties, which in addition to those discussed above also include the uncertainty from event plane resolution determination. The measured  $v_2$  depends on the  $p_T$  distribution of the reconstructed J/ψ, which could vary with the centrality of the collision. Therefore,  $\langle p_T \rangle^{uncor}$  of the reconstructed J/ψ is also shown in Fig. 3 (b) as a function of  $\langle N_{part} \rangle$ . For the most central collisions, 5%–20% and 20%–40% the inclusive J/ψ  $v_2$  for  $1.5 \leq p_T < 10$  GeV/c are  $0.101 \pm 0.044(\text{stat.}) \pm 0.032(\text{syst.})$  and  $0.116 \pm 0.045(\text{stat.}) \pm 0.041(\text{syst.})$ , respectively. The combined significance of a non-zero  $v_2$  measurement is  $2.9\sigma$ . For most peripheral Pb-Pb collisions, i.e. the two classes with low  $\langle N_{part} \rangle$  values, the  $v_2$  is consistent with zero within uncertainties. Although there is a



**Fig. 4:** (Color online) Inclusive J/ψ  $v_2(p_T)$  for semi-central (20%–60%) Pb-Pb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV. The  $v_2$  was measured in the  $p_T$  ranges: 0–2, 2–4, 4–6 and 6–10 GeV/c and the points are located at the measured  $\langle p_T \rangle^{\text{uncor}}$ . Calculations from two transport models [22] and [23] in the same kinematic range are also shown (see text for details).

small variation with centrality, the  $\langle p_T \rangle^{\text{uncor}}$  stays in the range 3.0–3.3 GeV/c indicating that the bulk of the reconstructed J/ψ are in the same  $p_T$  range for all centralities. Thus, the observed centrality dependence of the  $v_2$  for inclusive J/ψ with  $1.5 \leq p_T < 10$  GeV/c does not result from any bias in the sampled  $p_T$  distributions. For J/ψ with  $p_T < 1.5$  GeV/c (not shown) the  $v_2$  was found to be compatible with zero within one standard deviation for the four centrality classes. The  $\langle p_T \rangle^{\text{uncor}}$  ranges from about 0.75 to 0.9 GeV/c.

To allow a direct comparison with current model calculations, the inclusive J/ψ  $v_2(p_T)$  was also calculated in a broader centrality range, namely 20%–60%. Figure 4 shows the inclusive J/ψ  $v_2(p_T)$  for non-central (20%–60%) Pb-Pb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV. In this broader centrality range, the measured  $v_2$  signal in the  $p_T$  range 2–4 GeV/c deviates from zero by  $2\sigma$ . The same trend of  $v_2(p_T)$  is observed in the 20%–60% and in the 20%–40% centrality classes. This trend is different from the STAR measurement [15] at lower collision energy, which is compatible with zero for  $p_T \geq 2$  GeV/c albeit in somewhat different (10%–50% and 0%–80%) centrality ranges. Also shown in Fig. 4 are two transport model calculations that include a J/ψ regeneration component from deconfined charm quarks in the medium [22, 23]. In both models about 30% of the measured J/ψ in the 20%–60% centrality range are regenerated. On the one hand, thermalized charm quarks in the medium transfer a significant elliptic flow to regenerated J/ψ. On the other hand, initial J/ψ emitted out-of-plane traverse a longer path through the medium than those emitted in-plane resulting in a small apparent  $v_2$ . The predicted maximum  $v_2$  at  $p_T \sim 2.5$  GeV/c results from an interplay between the regeneration component, dominant at lower  $p_T$ , and the initial J/ψ component which takes over at higher  $p_T$ . The first model [22] is shown for the hypothesis of thermalization (full line) and non-thermalization (dashed line) of b quarks. The LHCb

Collaboration measured the fraction of J/ψ from B hadron decays in pp collisions at  $\sqrt{s} = 2.76$  and 7 TeV [24, 25] in the rapidity acceptance used for this measurement. At 7 TeV this fraction increases from about 7% at  $p_T \sim 0$  to 15% at  $p_T \sim 7$  GeV/c, while at 2.76 TeV it is about 7% for  $p_T < 12$  GeV/c. In Pb-Pb collisions this fraction could increase to a maximum of 11% if the B hadron  $R_{AA}$  is equal to 1. If b quarks do thermalize then their elliptic flow will be transferred to B mesons at hadronization and to the J/ψ at the B meson decay. In the second model [23] (dash-dotted line) only the case assuming thermalization of the b quark is shown. Both models are able to qualitatively describe the  $p_T$  dependence of the  $v_2$  and the nuclear modification factor of inclusive J/ψ [4].

In summary, we reported the ALICE measurement of inclusive J/ψ elliptic flow in the range  $0 \leq p_T < 10$  GeV/c at forward rapidity in Pb-Pb collisions at  $\sqrt{s_{NN}}=2.76$  TeV. For semi-central collisions indications of a non-zero J/ψ  $v_2$  are observed in the intermediate  $p_T$  range. This measurement complements the results on the J/ψ nuclear modification factor, where a smaller suppression was seen at low transverse momentum at the LHC compared to RHIC. These results suggest that a significant fraction of the observed J/ψ is produced from deconfined charm quarks in the QGP phase.

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E. Abbas<sup>1</sup>, B. Abelev<sup>72</sup>, J. Adam<sup>38</sup>, D. Adamová<sup>79</sup>, A.M. Adare<sup>129</sup>, M.M. Aggarwal<sup>83</sup>, G. Aglieri Rinella<sup>34</sup>, M. Agnello<sup>100,89</sup>, A.G. Agocs<sup>128</sup>, A. Agostinelli<sup>28</sup>, Z. Ahammed<sup>123</sup>, N. Ahmad<sup>18</sup>, A. Ahmad Masoodi<sup>18</sup>, S.A. Ahn<sup>65</sup>, S.U. Ahn<sup>65</sup>, I. Aimo<sup>25,100,89</sup>, M. Ajaz<sup>16</sup>, A. Akindinov<sup>51</sup>, D. Aleksandrov<sup>95</sup>, B. Alessandro<sup>100</sup>, A. Alici<sup>102,13</sup>, A. Alkin<sup>4</sup>, E. Almaráz Aviña<sup>61</sup>, J. Alme<sup>36</sup>, T. Alt<sup>40</sup>, V. Altini<sup>32</sup>, S. Altinpinar<sup>19</sup>, I. Altsybeev<sup>125</sup>, C. Andrei<sup>75</sup>, A. Andronic<sup>92</sup>, V. Anguelov<sup>88</sup>, J. Anielski<sup>59</sup>, C. Anson<sup>20</sup>, T. Antičić<sup>93</sup>, F. Antinori<sup>101</sup>, P. Antonioli<sup>102</sup>, L. Aphecetche<sup>108</sup>, H. Appelshäuser<sup>57</sup>, N. 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Beck<sup>57</sup>, N.K. Behera<sup>45</sup>, I. Belikov<sup>62</sup>, F. Bellini<sup>28</sup>, R. Bellwied<sup>118</sup>, E. Belmont-Moreno<sup>61</sup>, G. Bencedi<sup>128</sup>, S. Beole<sup>25</sup>, I. Berceau<sup>75</sup>, A. Bercuci<sup>75</sup>, Y. Berdnikov<sup>81</sup>, D. Berenyi<sup>128</sup>, A.A.E. Bergognon<sup>108</sup>, R.A. Bertens<sup>50</sup>, D. Berzano<sup>25,100</sup>, L. Betev<sup>34</sup>, A. Bhasin<sup>86</sup>, A.K. Bhati<sup>83</sup>, J. Bhom<sup>121</sup>, N. Bianchi<sup>69</sup>, L. Bianchi<sup>25</sup>, C. Bianchin<sup>50</sup>, J. Bielčik<sup>38</sup>, J. Bielčiková<sup>79</sup>, A. Bilandzic<sup>77</sup>, S. Bjelogrić<sup>50</sup>, F. Blanco<sup>118</sup>, F. Blanco<sup>11</sup>, D. Blau<sup>95</sup>, C. Blume<sup>57</sup>, M. Bocciaoli<sup>34</sup>, S. Böttger<sup>56</sup>, A. Bogdanov<sup>73</sup>, H. Bøggild<sup>77</sup>, M. Bogolyubsky<sup>48</sup>, L. Boldizsár<sup>128</sup>, M. Bombara<sup>39</sup>, J. Book<sup>57</sup>, H. Borel<sup>15</sup>, A. Borissov<sup>127</sup>, F. Bossu<sup>85</sup>, M. Botje<sup>78</sup>, E. Botta<sup>25</sup>, E. Braidot<sup>71</sup>, P. Braun-Munzinger<sup>92</sup>, M. Bregant<sup>108</sup>, T. Breitner<sup>56</sup>, T.A. Broker<sup>57</sup>, T.A. Browning<sup>90</sup>, M. Broz<sup>37</sup>, R. Brun<sup>34</sup>, E. Bruna<sup>25,100</sup>, G.E. Bruno<sup>32</sup>, D. Budnikov<sup>94</sup>, H. Buesching<sup>57</sup>, S. Bufalino<sup>25,100</sup>, P. Buncic<sup>34</sup>, O. Busch<sup>88</sup>, Z. Buthelezi<sup>85</sup>, D. Caffarri<sup>29,101</sup>, X. Cai<sup>8</sup>, H. Caines<sup>129</sup>, E. Calvo Villar<sup>98</sup>, P. Camerini<sup>23</sup>, V. Canoa Roman<sup>12</sup>, G. Cara Romeo<sup>102</sup>, W. Carena<sup>34</sup>, F. Carena<sup>34</sup>, N. Carlin Filho<sup>115</sup>, F. Carminati<sup>34</sup>, A. Casanova Díaz<sup>69</sup>, J. Castillo Castellanos<sup>15</sup>, J.F. Castillo Hernandez<sup>92</sup>, E.A.R. Casula<sup>24</sup>, V. Catanesu<sup>75</sup>, C. Cavicchioli<sup>34</sup>, C. Ceballos Sanchez<sup>10</sup>, J. Cepila<sup>38</sup>, P. Cerello<sup>100</sup>, B. Chang<sup>43,131</sup>, S. Chapeland<sup>34</sup>, J.L. Charvet<sup>15</sup>, S. Chattopadhyay<sup>96</sup>, S. Chattopadhyay<sup>123</sup>, M. Cherney<sup>82</sup>, C. Cheshkov<sup>34,117</sup>, B. Cheynis<sup>117</sup>, V. Chibante Barroso<sup>34</sup>, D.D. Chinellato<sup>118</sup>, P. Chochula<sup>34</sup>, M. Chojnacki<sup>77</sup>, S. Choudhury<sup>123</sup>, P. Christakoglou<sup>78</sup>, C.H. Christensen<sup>77</sup>, P. Christiansen<sup>33</sup>, T. Chujo<sup>121</sup>, S.U. Chung<sup>91</sup>, C. Cicalo<sup>103</sup>, L. Cifarelli<sup>28,13</sup>, F. Cindolo<sup>102</sup>, J. Cleymans<sup>85</sup>, F. Colamaria<sup>32</sup>, D. Colella<sup>32</sup>, A. Collu<sup>24</sup>, G. Conesa Balbastre<sup>68</sup>, Z. Conesa del Valle<sup>34,47</sup>, M.E. Connors<sup>129</sup>, G. Contin<sup>23</sup>, J.G. Contreras<sup>12</sup>, T.M. Cormier<sup>127</sup>, Y. Corrales Morales<sup>25</sup>, P. 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Mudnic<sup>110</sup>, S. Muhuri<sup>123</sup>, M. Mukherjee<sup>123</sup>, H. Müller<sup>34</sup>, M.G. Munhoz<sup>115</sup>, S. Murray<sup>85</sup>, L. Musa<sup>34</sup>, J. Musinsky<sup>52</sup>, B.K. Nandi<sup>45</sup>, R. Nania<sup>102</sup>, E. Nappi<sup>105</sup>, C. Nattrass<sup>119</sup>, T.K. Nayak<sup>123</sup>, S. Nazarenko<sup>94</sup>, A. Nedosekin<sup>51</sup>, M. Nicassio<sup>32,92</sup>, M. Niculescu<sup>55,34</sup>, B.S. Nielsen<sup>77</sup>, T. Niida<sup>121</sup>, S. Nikolaev<sup>95</sup>, V. Nikolic<sup>93</sup>, S. Nikulin<sup>95</sup>, V. Nikulin<sup>81</sup>, B.S. Nilsen<sup>82</sup>, M.S. Nilsson<sup>22</sup>, F. Noferini<sup>102,13</sup>, P. Nomokonov<sup>63</sup>, G. Nooren<sup>50</sup>, A. Nyanin<sup>95</sup>, A. Nyatha<sup>45</sup>, C. Nygaard<sup>77</sup>, J. Nystrand<sup>19</sup>, A. Ochirov<sup>125</sup>, H. Oeschler<sup>58,34,88</sup>, S. Oh<sup>129</sup>, S.K. Oh<sup>41</sup>, J. Oleniacz<sup>126</sup>, A.C. Oliveira Da Silva<sup>115</sup>, C. Oppedisano<sup>100</sup>, A. Ortiz Velasquez<sup>33,60</sup>, A. Oskarsson<sup>33</sup>, P. Ostrowski<sup>126</sup>, J. Otwinowski<sup>92</sup>, K. Oyama<sup>88</sup>, K. Ozawa<sup>120</sup>, Y. Pachmayer<sup>88</sup>, M. Pachr<sup>38</sup>, F. Padilla<sup>25</sup>, P. Pagano<sup>30</sup>, G. Paic<sup>60</sup>, F. Painke<sup>40</sup>, C. Pajares<sup>17</sup>, S.K. Pal<sup>123</sup>, A. Palaha<sup>97</sup>, A. Palmeri<sup>99</sup>, V. Papikyan<sup>2</sup>, G.S. Pappalardo<sup>99</sup>, W.J. Park<sup>92</sup>, A. Passfeld<sup>59</sup>, D.I. Patalakha<sup>48</sup>, V. Paticchio<sup>105</sup>, B. Paul<sup>96</sup>, A. Pavlinov<sup>127</sup>, T. Pawlak<sup>126</sup>, T. Peitzmann<sup>50</sup>, H. Pereira Da Costa<sup>15</sup>, E. Pereira De Oliveira Filho<sup>115</sup>, D. Peresunko<sup>95</sup>, C.E. Pérez Lara<sup>78</sup>, D. Perrino<sup>32</sup>, W. Peryt<sup>126</sup>, A. Pesci<sup>102</sup>, Y. Pestov<sup>6</sup>, V. Petráček<sup>38</sup>, M. Petran<sup>38</sup>, M. Petris<sup>75</sup>, P. Petrov<sup>97</sup>, M. Petrovici<sup>75</sup>, C. Petta<sup>27</sup>, S. Piano<sup>104</sup>, M. Pikna<sup>37</sup>, P. Pillot<sup>108</sup>, O. Pinazza<sup>34</sup>, L. Pinsky<sup>118</sup>, N. Pitz<sup>57</sup>, D.B. Piyarathna<sup>118</sup>, M. Planinic<sup>93</sup>, M. Płoskoń<sup>71</sup>, J. Pluta<sup>126</sup>, T. Pocheptsov<sup>63</sup>, S. Pochybova<sup>128</sup>, P.L.M. Podesta-Lerma<sup>114</sup>, M.G. Poghosyan<sup>34</sup>, K. Polák<sup>54</sup>, B. Polichtchouk<sup>48</sup>, N. Poljak<sup>50,93</sup>, A. Pop<sup>75</sup>, S. Porteboeuf-Houssais<sup>67</sup>, V. Pospíšil<sup>38</sup>, B. Potukuchi<sup>86</sup>, S.K. Prasad<sup>127</sup>, R. Preghenella<sup>102,13</sup>, F. Prino<sup>100</sup>, C.A. Pruneau<sup>127</sup>, I. Pshenichnov<sup>49</sup>, G. Puddu<sup>24</sup>, V. Punin<sup>94</sup>, M. Putis<sup>39</sup>, J. Putschke<sup>127</sup>, H. Qvigstad<sup>22</sup>, A. Rachevski<sup>104</sup>, A. Rademakers<sup>34</sup>, T.S. Rähä<sup>43</sup>, J. Rak<sup>43</sup>, A. Rakotozafindrabe<sup>15</sup>, L. Ramello<sup>31</sup>, S. Raniwala<sup>87</sup>, R. Raniwala<sup>87</sup>, S.S. Räsänen<sup>43</sup>, B.T. Rascanu<sup>57</sup>, D. Rathee<sup>83</sup>, W. Rauch<sup>34</sup>, K.F. Read<sup>119</sup>, J.S. Real<sup>68</sup>, K. Redlich<sup>74,iii</sup>, R.J. Reed<sup>129</sup>, A. Rehman<sup>19</sup>, P. Reichelt<sup>57</sup>, M. Reicher<sup>50</sup>, R. Renfordt<sup>57</sup>, A.R. Reolon<sup>69</sup>, A. Reshetin<sup>49</sup>, F. Rettig<sup>40</sup>, J.-P. Revol<sup>34</sup>, K. Reygers<sup>88</sup>, L. Riccati<sup>100</sup>, R.A. Ricci<sup>70</sup>, T. Richert<sup>33</sup>, M. Richter<sup>22</sup>, P. Riedler<sup>34</sup>, W. Riegler<sup>34</sup>, F. Riggi<sup>27,99</sup>, M. Rodríguez Cahuantzi<sup>3</sup>, A. Rodriguez Manso<sup>78</sup>, K. Røed<sup>19,22</sup>, E. Rogochaya<sup>63</sup>, D. Rohr<sup>40</sup>, D. Röhrich<sup>19</sup>, R. Romita<sup>92,107</sup>,

F. Ronchetti<sup>69</sup>, P. Rosnet<sup>67</sup>, S. Rossegger<sup>34</sup>, A. Rossi<sup>34,29</sup>, P. Roy<sup>96</sup>, C. Roy<sup>62</sup>, A.J. Rubio Montero<sup>11</sup>, R. Rui<sup>23</sup>, R. Russo<sup>25</sup>, E. Ryabinkin<sup>95</sup>, A. Rybicki<sup>112</sup>, S. Sadovsky<sup>48</sup>, K. Šafařík<sup>34</sup>, R. Sahoo<sup>46</sup>, P.K. Sahu<sup>53</sup>, J. Saini<sup>123</sup>, H. Sakaguchi<sup>44</sup>, S. Sakai<sup>71</sup>, D. Sakata<sup>121</sup>, C.A. Salgado<sup>17</sup>, J. Salzwedel<sup>20</sup>, S. Sambyal<sup>86</sup>, V. Samsonov<sup>81</sup>, X. Sanchez Castro<sup>62</sup>, L. Šándor<sup>52</sup>, A. Sandoval<sup>61</sup>, M. Sano<sup>121</sup>, G. Santagati<sup>27</sup>, R. Santoro<sup>34,13</sup>, J. Sarkamo<sup>43</sup>, D. Sarkar<sup>123</sup>, E. Scapparone<sup>102</sup>, F. Scarlassara<sup>29</sup>, R.P. Scharenberg<sup>90</sup>, C. Schiaua<sup>75</sup>, R. Schicker<sup>88</sup>, H.R. Schmidt<sup>122</sup>, C. Schmidt<sup>92</sup>, S. Schuchmann<sup>57</sup>, J. Schukraft<sup>34</sup>, T. Schuster<sup>129</sup>, Y. Schutz<sup>34,108</sup>, K. Schwarz<sup>92</sup>, K. Schweda<sup>92</sup>, G. Scioli<sup>28</sup>, E. Scomparin<sup>100</sup>, R. Scott<sup>119</sup>, P.A. Scott<sup>97</sup>, G. Segato<sup>29</sup>, I. Selyuzhenkov<sup>92</sup>, S. Senyukov<sup>62</sup>, J. Seo<sup>91</sup>, S. Serici<sup>24</sup>, E. Serradilla<sup>11,61</sup>, A. Sevcenco<sup>55</sup>, A. Shabetai<sup>108</sup>, G. Shabratova<sup>63</sup>, R. Shahoyan<sup>34</sup>, N. Sharma<sup>119</sup>, S. Sharma<sup>86</sup>, S. Rohni<sup>86</sup>, K. Shigaki<sup>44</sup>, K. Shtejer<sup>10</sup>, Y. Sibirak<sup>95</sup>, E. Sicking<sup>59</sup>, S. Siddhanta<sup>103</sup>, T. Siemiarczuk<sup>74</sup>, D. Silvermyr<sup>80</sup>, C. Silvestre<sup>68</sup>, G. Simatovic<sup>60,93</sup>, G. Simonetti<sup>34</sup>, R. Singaraju<sup>123</sup>, R. Singh<sup>86</sup>, S. Singha<sup>123,76</sup>, V. Singhal<sup>123</sup>, B.C. Sinha<sup>123</sup>, T. Sinha<sup>96</sup>, B. Sitar<sup>37</sup>, M. Sitta<sup>31</sup>, T.B. Skaali<sup>22</sup>, K. Skjerdal<sup>19</sup>, R. Smakal<sup>38</sup>, N. Smirnov<sup>129</sup>, R.J.M. Snellings<sup>50</sup>, C. Sogaard<sup>33</sup>, R. Soltz<sup>72</sup>, M. Song<sup>131</sup>, J. Song<sup>91</sup>, C. Soos<sup>34</sup>, F. Soramel<sup>29</sup>, I. Sputowska<sup>112</sup>, M. Spyropoulou-Stassinaki<sup>84</sup>, B.K. Srivastava<sup>90</sup>, J. Stachel<sup>88</sup>, I. Stan<sup>55</sup>, G. Stefanek<sup>74</sup>, M. Steinpreis<sup>20</sup>, E. Stenlund<sup>33</sup>, G. Steyn<sup>85</sup>, J.H. Stiller<sup>88</sup>, D. Stocco<sup>108</sup>, M. Stolpovskiy<sup>48</sup>, P. Strmen<sup>37</sup>, A.A.P. Suaide<sup>115</sup>, M.A. Subieta Vásquez<sup>25</sup>, T. Sugitate<sup>44</sup>, C. Suire<sup>47</sup>, R. Sultanov<sup>51</sup>, M. Šumbera<sup>79</sup>, T. Susa<sup>93</sup>, T.J.M. Symons<sup>71</sup>, A. Szanto de Toledo<sup>115</sup>, I. Szarka<sup>37</sup>, A. Szczepankiewicz<sup>112,34</sup>, M. Szymański<sup>126</sup>, J. Takahashi<sup>116</sup>, M.A. Tangaro<sup>32</sup>, J.D. Tapia Takaki<sup>47</sup>, A. Tarantola Peloni<sup>57</sup>, A. Tarazona Martinez<sup>34</sup>, A. Tauro<sup>34</sup>, G. Tejeda Muñoz<sup>3</sup>, A. Telesca<sup>34</sup>, A. Ter Minasyan<sup>95</sup>, C. Terrevoli<sup>32</sup>, J. Thäder<sup>92</sup>, D. Thomas<sup>50</sup>, R. Tieulent<sup>117</sup>, A.R. Timmins<sup>118</sup>, D. Tlusty<sup>38</sup>, A. Toia<sup>40,29,101</sup>, H. Torii<sup>120</sup>, L. Toscano<sup>100</sup>, V. Trubnikov<sup>4</sup>, D. Truesdale<sup>20</sup>, W.H. Trzaska<sup>43</sup>, T. Tsuji<sup>120</sup>, A. Tumkin<sup>94</sup>, R. Turrisi<sup>101</sup>, T.S. Tveter<sup>22</sup>, J. Ulery<sup>57</sup>, K. Ullaland<sup>19</sup>, J. Ulrich<sup>64,56</sup>, A. Uras<sup>117</sup>, G.M. Urciuoli<sup>106</sup>, G.L. Usai<sup>24</sup>, M. Vajzer<sup>38,79</sup>, M. Vala<sup>63,52</sup>, L. Valencia Palomo<sup>47</sup>, P. Vande Vyvre<sup>34</sup>, J.W. Van Hoorne<sup>34</sup>, M. van Leeuwen<sup>50</sup>, L. Vannucci<sup>70</sup>, A. Vargas<sup>3</sup>, R. Varma<sup>45</sup>, M. Vasileiou<sup>84</sup>, A. Vasiliev<sup>95</sup>, V. Vechernin<sup>125</sup>, M. Veldhoen<sup>50</sup>, M. Venaruzzo<sup>23</sup>, E. Vercellin<sup>25</sup>, S. Vergara<sup>3</sup>, R. Vernet<sup>9</sup>, M. Verweij<sup>50</sup>, L. Vickovic<sup>110</sup>, G. Viesti<sup>29</sup>, J. Viinikainen<sup>43</sup>, Z. Vilakazi<sup>85</sup>, O. Villalobos Baillie<sup>97</sup>, Y. Vinogradov<sup>94</sup>, L. Vinogradov<sup>125</sup>, A. Vinogradov<sup>95</sup>, T. Virgili<sup>30</sup>, Y.P. Viyogi<sup>123</sup>, A. Vodopyanov<sup>63</sup>, M.A. Völkl<sup>88</sup>, S. Voloshin<sup>127</sup>, K. Voloshin<sup>51</sup>, G. Volpe<sup>34</sup>, B. von Haller<sup>34</sup>, I. Vorobyev<sup>125</sup>, D. Vranic<sup>92,34</sup>, J. Vrláková<sup>39</sup>, B. Vulpescu<sup>67</sup>, A. Vyushin<sup>94</sup>, B. Wagner<sup>19</sup>, V. Wagner<sup>38</sup>, R. Wan<sup>8</sup>, Y. Wang<sup>8</sup>, M. Wang<sup>8</sup>, Y. Wang<sup>88</sup>, K. Watanabe<sup>121</sup>, M. Weber<sup>118</sup>, J.P. Wessels<sup>34,59</sup>, U. Westerhoff<sup>59</sup>, J. Wiechula<sup>122</sup>, J. Wikne<sup>22</sup>, M. Wilde<sup>59</sup>, G. Wilk<sup>74</sup>, M.C.S. Williams<sup>102</sup>, B. Windelband<sup>88</sup>, L. Xaplanteris Karampatsos<sup>113</sup>, C.G. Yaldo<sup>127</sup>, Y. Yamaguchi<sup>120</sup>, S. Yang<sup>19</sup>, P. Yang<sup>8</sup>, H. Yang<sup>15,50</sup>, S. Yasnopolskiy<sup>95</sup>, J. Yi<sup>91</sup>, Z. Yin<sup>8</sup>, I.-K. Yoo<sup>91</sup>, J. Yoon<sup>131</sup>, W. Yu<sup>57</sup>, X. Yuan<sup>8</sup>, I. Yushmanov<sup>95</sup>, V. Zaccaro<sup>77</sup>, C. Zach<sup>38</sup>, C. Zampolli<sup>102</sup>, S. Zaporozhets<sup>63</sup>, A. Zarochentsev<sup>125</sup>, P. Závada<sup>54</sup>, N. Zaviyalov<sup>94</sup>, H. Zbroszczyk<sup>126</sup>, P. Zelnicsek<sup>56</sup>, I.S. Zgura<sup>55</sup>, M. Zhalov<sup>81</sup>, H. Zhang<sup>8</sup>, X. Zhang<sup>71,67,8</sup>, Y. Zhang<sup>8</sup>, D. Zhou<sup>8</sup>, F. Zhou<sup>8</sup>, Y. Zhou<sup>50</sup>, H. Zhu<sup>8</sup>, J. Zhu<sup>8</sup>, X. Zhu<sup>8</sup>, J. Zhu<sup>8</sup>, A. Zichichi<sup>28,13</sup>, A. Zimmermann<sup>88</sup>, G. Zinovjev<sup>4</sup>, Y. Zoccarato<sup>117</sup>, M. Zynovyev<sup>4</sup>, M. Zyzak<sup>57</sup>

## Affiliation notes

- <sup>i</sup> Also at: M.V.Lomonosov Moscow State University, D.V.Skobeltzyn Institute of Nuclear Physics, Moscow, Russia
- <sup>ii</sup> Also at: University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
- <sup>iii</sup> Also at: Institute of Theoretical Physics, University of Wrocław, Wrocław, Poland

## Collaboration Institutes

- <sup>1</sup> Academy of Scientific Research and Technology (ASRT), Cairo, Egypt
- <sup>2</sup> A. I. Alikhanyan National Science Laboratory (Yerevan Physics Institute) Foundation, Yerevan, Armenia
- <sup>3</sup> Benemérita Universidad Autónoma de Puebla, Puebla, Mexico
- <sup>4</sup> Bogolyubov Institute for Theoretical Physics, Kiev, Ukraine
- <sup>5</sup> Bose Institute, Department of Physics and Centre for Astroparticle Physics and Space Science (CAPSS), Kolkata, India
- <sup>6</sup> Budker Institute for Nuclear Physics, Novosibirsk, Russia
- <sup>7</sup> California Polytechnic State University, San Luis Obispo, California, United States
- <sup>8</sup> Central China Normal University, Wuhan, China
- <sup>9</sup> Centre de Calcul de l'IN2P3, Villeurbanne, France
- <sup>10</sup> Centro de Aplicaciones Tecnológicas y Desarrollo Nuclear (CEADEN), Havana, Cuba

- 11 Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
- 12 Centro de Investigación y de Estudios Avanzados (CINVESTAV), Mexico City and Mérida, Mexico
- 13 Centro Fermi - Museo Storico della Fisica e Centro Studi e Ricerche “Enrico Fermi”, Rome, Italy
- 14 Chicago State University, Chicago, United States
- 15 Commissariat à l’Energie Atomique, IRFU, Saclay, France
- 16 COMSATS Institute of Information Technology (CIIT), Islamabad, Pakistan
- 17 Departamento de Física de Partículas and IGFAE, Universidad de Santiago de Compostela, Santiago de Compostela, Spain
- 18 Department of Physics Aligarh Muslim University, Aligarh, India
- 19 Department of Physics and Technology, University of Bergen, Bergen, Norway
- 20 Department of Physics, Ohio State University, Columbus, Ohio, United States
- 21 Department of Physics, Sejong University, Seoul, South Korea
- 22 Department of Physics, University of Oslo, Oslo, Norway
- 23 Dipartimento di Fisica dell’Università and Sezione INFN, Trieste, Italy
- 24 Dipartimento di Fisica dell’Università and Sezione INFN, Cagliari, Italy
- 25 Dipartimento di Fisica dell’Università and Sezione INFN, Turin, Italy
- 26 Dipartimento di Fisica dell’Università ‘La Sapienza’ and Sezione INFN, Rome, Italy
- 27 Dipartimento di Fisica e Astronomia dell’Università and Sezione INFN, Catania, Italy
- 28 Dipartimento di Fisica e Astronomia dell’Università and Sezione INFN, Bologna, Italy
- 29 Dipartimento di Fisica e Astronomia dell’Università and Sezione INFN, Padova, Italy
- 30 Dipartimento di Fisica ‘E.R. Caianiello’ dell’Università and Gruppo Collegato INFN, Salerno, Italy
- 31 Dipartimento di Scienze e Innovazione Tecnologica dell’Università del Piemonte Orientale and Gruppo Collegato INFN, Alessandria, Italy
- 32 Dipartimento Interateneo di Fisica ‘M. Merlin’ and Sezione INFN, Bari, Italy
- 33 Division of Experimental High Energy Physics, University of Lund, Lund, Sweden
- 34 European Organization for Nuclear Research (CERN), Geneva, Switzerland
- 35 Fachhochschule Köln, Köln, Germany
- 36 Faculty of Engineering, Bergen University College, Bergen, Norway
- 37 Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava, Slovakia
- 38 Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Prague, Czech Republic
- 39 Faculty of Science, P.J. Šafárik University, Košice, Slovakia
- 40 Frankfurt Institute for Advanced Studies, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany
- 41 Gangneung-Wonju National University, Gangneung, South Korea
- 42 Gauhati University, Department of Physics, Guwahati, India
- 43 Helsinki Institute of Physics (HIP) and University of Jyväskylä, Jyväskylä, Finland
- 44 Hiroshima University, Hiroshima, Japan
- 45 Indian Institute of Technology Bombay (IIT), Mumbai, India
- 46 Indian Institute of Technology Indore, Indore, India (ITI)
- 47 Institut de Physique Nucléaire d’Orsay (IPNO), Université Paris-Sud, CNRS-IN2P3, Orsay, France
- 48 Institute for High Energy Physics, Protvino, Russia
- 49 Institute for Nuclear Research, Academy of Sciences, Moscow, Russia
- 50 Nikhef, National Institute for Subatomic Physics and Institute for Subatomic Physics of Utrecht University, Utrecht, Netherlands
- 51 Institute for Theoretical and Experimental Physics, Moscow, Russia
- 52 Institute of Experimental Physics, Slovak Academy of Sciences, Košice, Slovakia
- 53 Institute of Physics, Bhubaneswar, India
- 54 Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic
- 55 Institute of Space Sciences (ISS), Bucharest, Romania
- 56 Institut für Informatik, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany
- 57 Institut für Kernphysik, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany
- 58 Institut für Kernphysik, Technische Universität Darmstadt, Darmstadt, Germany
- 59 Institut für Kernphysik, Westfälische Wilhelms-Universität Münster, Münster, Germany
- 60 Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, Mexico City, Mexico
- 61 Instituto de Física, Universidad Nacional Autónoma de México, Mexico City, Mexico

- <sup>62</sup> Institut Pluridisciplinaire Hubert Curien (IPHC), Université de Strasbourg, CNRS-IN2P3, Strasbourg, France
- <sup>63</sup> Joint Institute for Nuclear Research (JINR), Dubna, Russia
- <sup>64</sup> Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
- <sup>65</sup> Korea Institute of Science and Technology Information, Daejeon, South Korea
- <sup>66</sup> KTO Karatay University, Konya, Turkey
- <sup>67</sup> Laboratoire de Physique Corpusculaire (LPC), Clermont Université, Université Blaise Pascal, CNRS-IN2P3, Clermont-Ferrand, France
- <sup>68</sup> Laboratoire de Physique Subatomique et de Cosmologie (LPSC), Université Joseph Fourier, CNRS-IN2P3, Institut Polytechnique de Grenoble, Grenoble, France
- <sup>69</sup> Laboratori Nazionali di Frascati, INFN, Frascati, Italy
- <sup>70</sup> Laboratori Nazionali di Legnaro, INFN, Legnaro, Italy
- <sup>71</sup> Lawrence Berkeley National Laboratory, Berkeley, California, United States
- <sup>72</sup> Lawrence Livermore National Laboratory, Livermore, California, United States
- <sup>73</sup> Moscow Engineering Physics Institute, Moscow, Russia
- <sup>74</sup> National Centre for Nuclear Studies, Warsaw, Poland
- <sup>75</sup> National Institute for Physics and Nuclear Engineering, Bucharest, Romania
- <sup>76</sup> National Institute of Science Education and Research, Bhubaneswar, India
- <sup>77</sup> Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
- <sup>78</sup> Nikhef, National Institute for Subatomic Physics, Amsterdam, Netherlands
- <sup>79</sup> Nuclear Physics Institute, Academy of Sciences of the Czech Republic, Řež u Prahy, Czech Republic
- <sup>80</sup> Oak Ridge National Laboratory, Oak Ridge, Tennessee, United States
- <sup>81</sup> Petersburg Nuclear Physics Institute, Gatchina, Russia
- <sup>82</sup> Physics Department, Creighton University, Omaha, Nebraska, United States
- <sup>83</sup> Physics Department, Panjab University, Chandigarh, India
- <sup>84</sup> Physics Department, University of Athens, Athens, Greece
- <sup>85</sup> Physics Department, University of Cape Town and iThemba LABS, National Research Foundation, Somerset West, South Africa
- <sup>86</sup> Physics Department, University of Jammu, Jammu, India
- <sup>87</sup> Physics Department, University of Rajasthan, Jaipur, India
- <sup>88</sup> Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
- <sup>89</sup> Politecnico di Torino, Turin, Italy
- <sup>90</sup> Purdue University, West Lafayette, Indiana, United States
- <sup>91</sup> Pusan National University, Pusan, South Korea
- <sup>92</sup> Research Division and ExtreMe Matter Institute EMMI, GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany
- <sup>93</sup> Rudjer Bošković Institute, Zagreb, Croatia
- <sup>94</sup> Russian Federal Nuclear Center (VNIIEF), Sarov, Russia
- <sup>95</sup> Russian Research Centre Kurchatov Institute, Moscow, Russia
- <sup>96</sup> Saha Institute of Nuclear Physics, Kolkata, India
- <sup>97</sup> School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
- <sup>98</sup> Sección Física, Departamento de Ciencias, Pontificia Universidad Católica del Perú, Lima, Peru
- <sup>99</sup> Sezione INFN, Catania, Italy
- <sup>100</sup> Sezione INFN, Turin, Italy
- <sup>101</sup> Sezione INFN, Padova, Italy
- <sup>102</sup> Sezione INFN, Bologna, Italy
- <sup>103</sup> Sezione INFN, Cagliari, Italy
- <sup>104</sup> Sezione INFN, Trieste, Italy
- <sup>105</sup> Sezione INFN, Bari, Italy
- <sup>106</sup> Sezione INFN, Rome, Italy
- <sup>107</sup> Nuclear Physics Group, STFC Daresbury Laboratory, Daresbury, United Kingdom
- <sup>108</sup> SUBATECH, Ecole des Mines de Nantes, Université de Nantes, CNRS-IN2P3, Nantes, France
- <sup>109</sup> Suranaree University of Technology, Nakhon Ratchasima, Thailand
- <sup>110</sup> Technical University of Split FESB, Split, Croatia
- <sup>111</sup> Technische Universität München, Munich, Germany
- <sup>112</sup> The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Cracow, Poland

- <sup>113</sup> The University of Texas at Austin, Physics Department, Austin, TX, United States
- <sup>114</sup> Universidad Autónoma de Sinaloa, Culiacán, Mexico
- <sup>115</sup> Universidade de São Paulo (USP), São Paulo, Brazil
- <sup>116</sup> Universidade Estadual de Campinas (UNICAMP), Campinas, Brazil
- <sup>117</sup> Université de Lyon, Université Lyon 1, CNRS/IN2P3, IPN-Lyon, Villeurbanne, France
- <sup>118</sup> University of Houston, Houston, Texas, United States
- <sup>119</sup> University of Tennessee, Knoxville, Tennessee, United States
- <sup>120</sup> University of Tokyo, Tokyo, Japan
- <sup>121</sup> University of Tsukuba, Tsukuba, Japan
- <sup>122</sup> Eberhard Karls Universität Tübingen, Tübingen, Germany
- <sup>123</sup> Variable Energy Cyclotron Centre, Kolkata, India
- <sup>124</sup> Vestfold University College, Tonsberg, Norway
- <sup>125</sup> V. Fock Institute for Physics, St. Petersburg State University, St. Petersburg, Russia
- <sup>126</sup> Warsaw University of Technology, Warsaw, Poland
- <sup>127</sup> Wayne State University, Detroit, Michigan, United States
- <sup>128</sup> Wigner Research Centre for Physics, Hungarian Academy of Sciences, Budapest, Hungary
- <sup>129</sup> Yale University, New Haven, Connecticut, United States
- <sup>130</sup> Yildiz Technical University, Istanbul, Turkey
- <sup>131</sup> Yonsei University, Seoul, South Korea
- <sup>132</sup> Zentrum für Technologietransfer und Telekommunikation (ZTT), Fachhochschule Worms, Worms, Germany